PL-TR--91-3085

AD-A243 948

PL-TR--
91-3085

ARCJET FACILITY

Captain Salvador Castillo

October 1991

Final Report

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

91-16461

PHILLIPS LABORATORY
Propulsion Directorate
AIR FORCE SYSTEMS COMMAND
EDWARDS AIR FORCE BASE CA 93523-5000

NOTICE

When U.S. Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, or in any way licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may be related thereto.

FOREWORD

This final report was submitted on completion of this phase of JON: 305800RC by the OLAC PL/RCC Branch, at the Phillips Laboratory (AFSC), Edwards AFB CA 93523-5000. OLAC PL Project Manager was Salvador Castillo, Capt, USAF.

This report has been reviewed and is approved for release and distribution in accordance with the distribution statement on the cover and on the SF Form 298.

Salvador Castillo

SALVADOR CASTILLO, CAPT, USAF
Project Manager

Bernard R. Bornhorst

BERNARD R. BORNHORST
Chief, Space Engineering Branch

FOR THE COMMANDER

PETER A. VAN SPLINTER
Director,
Applications Engineering Division

RANNEY G. ADAMS
Public Affairs Director

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
September 1991

3. REPORT TYPE AND DATES COVERED
Final Aug 86 to Aug 91

4. TITLE AND SUBTITLE
ARCJET FACILITY

5. FUNDING NUMBERS
PE- 62302F
PR- 3058
TA- 00RC
WU- 342740

6. AUTHOR(S)
SALVADOR CASTILLO

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Phillips Laboratory (AFSC), Propulsion Directorate
OLAC PL/RAS
Edwards AFB CA 93523-5000

8. PERFORMING ORGANIZATION REPORT NUMBER
PL-TR-91-3085

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
COSATI CODES: 21/03; 21/05; 14/02

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
The Phillips Laboratory's Electric Propulsion Laboratory has designed and begun installation of an arcjet research facility. A 5 foot by 10 foot long chamber with eight 12 inch quartz windows will allow non-intrusive diagnostic research on arcjets. A 6 foot by 8 foot endurance test chamber will allow continuous testing of 5 to 100 kilowatt arcjets for up to 1500 hours. Each of the chambers will be equipped with the essential instrumentation to measure thruster operating conditions. This includes thrust, chamber pressure, chamber and propellant temperature, mass flow, current, and voltage. Video cameras will be used for plume visualizations.

14. SUBJECT TERMS
Electric Propulsion; Arcjet; Electrothermal Thruster; Rocket Test Facility; Thrust Measurement; Plasma Thruster

15. NUMBER OF PAGES
16

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

INTRODUCTION

This paper discusses the Phillips Laboratory's Electric Propulsion Laboratory (PLEPL) arcjet experimental facility. Experimental goals, facility components, and test procedure are described.

Background

The U.S. Air Force has a continual need for reliable access to space. This need includes requirements for heavy lift launch vehicles, flexible lower weight launch vehicles, orbital transfer vehicles, and station keeping thrusters. With the current high costs of space transportation, the Air Force is very interested in rocket propulsion technologies that yield the same access to space at a greatly reduced cost. One of the most promising of these new technologies is electric propulsion. Of arcjet, magnetoplasmadynamic (MPD), and ion thrusters, arcjet thrusters represent the best developed and nearest term technology. Arcjets can meet Air Force requirements for inexpensive, reliable orbital transfer vehicles.

An arcjet uses a high current arc between a cathode and an anode to heat a propellant which is then expanded through a conventional nozzle. Arcjets have specific impulses of 600-1200 seconds and efficiencies in the 40-60 percent range (Ref. 1). High arcjet specific impulse can nearly double payload mass taken from low earth orbit (LEO) to geosynchronous orbit (GEO), from the same launch vehicle (Ref. 2). The only possible drawback for arcjets is that thrust is on the order of 1 pound resulting in long trip times (around 150 days for typical LEO to GEO transfer).

A fair amount of arcjet research was conducted in the 1960s, but a lack of space power systems at the required multi-kilowatt levels led to a paucity of arcjet research in the late 1960s and 1970s (Ref 3). With space power levels expected up to 50 kWe by year 2000, arcjet research has begun anew. 30 kilowatt arcjets are now feasible and 100 kilowatt thrusters may soon be feasible. Arcjet thrust is proportional to thruster power so higher powers equate to shorter transfer times.

Little is presently understood about the physics of arcjet operation. Arcjets operate in a regime of low pressure, high temperature plasmas. The extremely high temperatures, coupled with long operating times and frequent on/off cycles, result in large erosion rates for electrode materials. The search for optimal thruster geometries and materials is an important research area related to the erosion problem.

Project Goals

The goal of the project is to build a facility to allow research on 5 to 100 kilowatt arcjets. This includes measurement of thrust, specific impulse, efficiency, and endurance testing.

The facility will also allow development of non-intrusive diagnostic techniques. The research done in the facility will result in improved arcjet designs, better understanding of arcjet physics, and improved electric propulsion diagnostic techniques.

FACILITY COMPONENTS

Vacuum System

The vacuum system that will serve the arcjet chambers is shown in Figure 1. The pump system will be interconnected to the various chambers, allowing a variety of pumping capabilities and test flexibility. The arcjet primary pumps are three pump packs. Each pump pack includes a roughing pump, blower pump and booster pump. The roughing pumps are Stokes Microvac (Model 412 H-10) mechanical pumps with a 300 cubic feet per minute (cfm) throughput (air). The blowers are Dresser (Model 615 RGS) Roots blowers. The large boosters are 19,000 cfm capacity Roots blowers (Model 1845 HVB). When all pumps are installed, they will be able to remove 1 gram per second of ammonia, while maintaining a vacuum pressure of 80-100 millitorr in the arcjet chambers. This is more than enough to allow true arcjet operation and justify measured arcjet performance (Ref 4).

Chambers

The arcjet facility consists of two chambers (Figs. 1,2). One will be used for diagnostic research and the other for long term endurance testing up to 1500 hrs. The diagnostic chamber is a rolled aluminum tank with a wall 1/2 inch thick. Built in-house at the Phillips Lab, the chamber is 10 feet long and has a 5 foot diameter. Manually opened, hinged doors are at both ends of the chamber (Fig. 3). Six view ports along the sides and one on each door will provide good coverage of the inside of the tank. Instrumentation, coolant and power feedthroughs are located along the top and bottom of the tank. The vacuum duct is centered at the very top of the chamber.

The optical test chamber windows are high quality Dynasil 1000 fused silica windows. These 1 inch thick, 13 inch diameter windows transmit 90 percent of light from 0.25 to 1.5 microns. This light transmittance is well in the range of any spectroscopic requirements that there might be for ultraviolet, visible, and infrared diagnostics.

Since the PLEPL will be conducting research on radiation cooled arcjets, much of the waste heat will be radiated to the chamber walls. Past experiments have shown that arcjet anode tips can reach temperatures of up to 2000 degrees Celsius (Ref. 5). To prevent this heat from damaging experimental apparatus, a set of cooling panels will be inserted into the chamber, forming an inner wall. The panels are 16 gauge stainless steel coil panels, using a water-glycol mix as coolant. The panels are formed into a four foot diameter, 7 foot long cylinder with flat 4 foot diame-

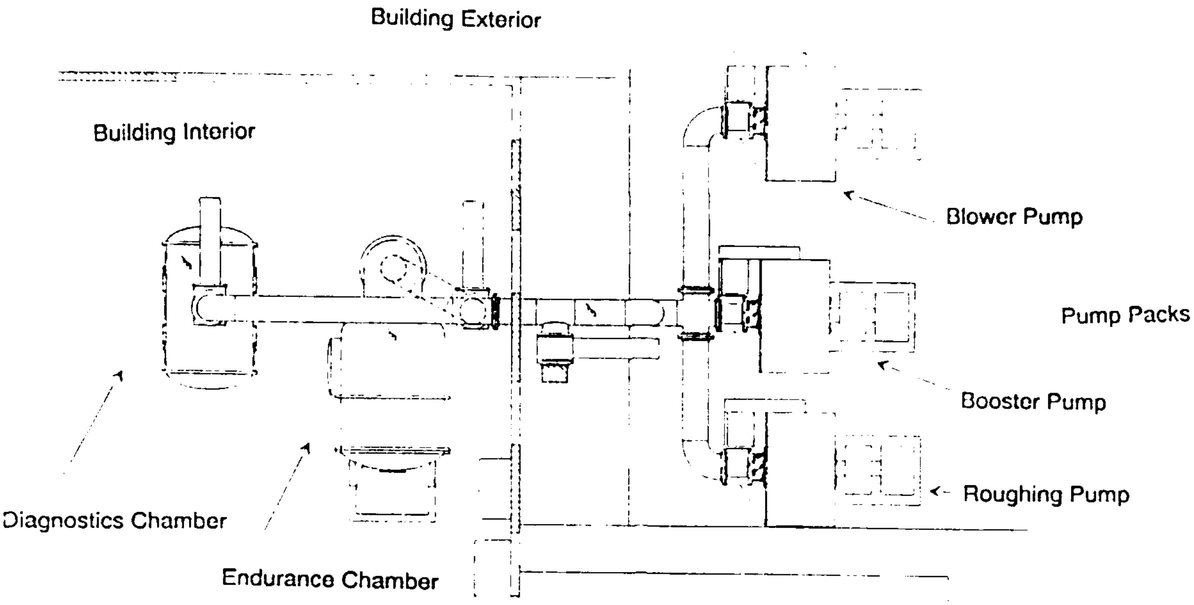


Figure 1
Arcjet Facility Layout

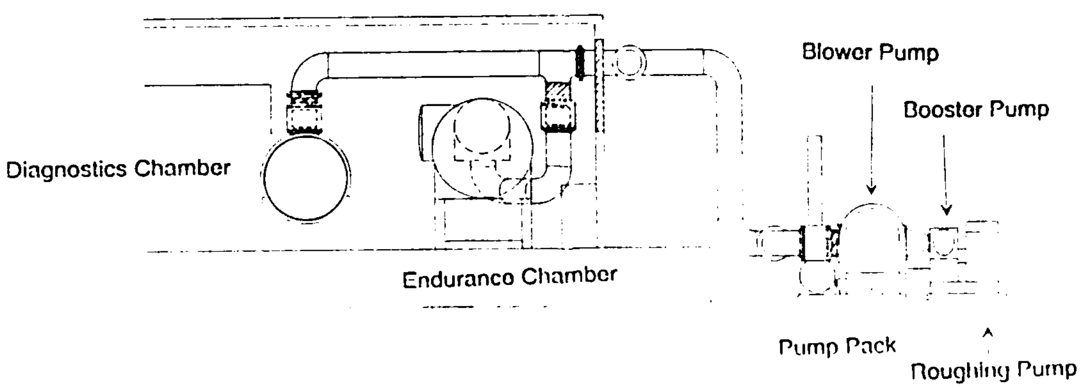
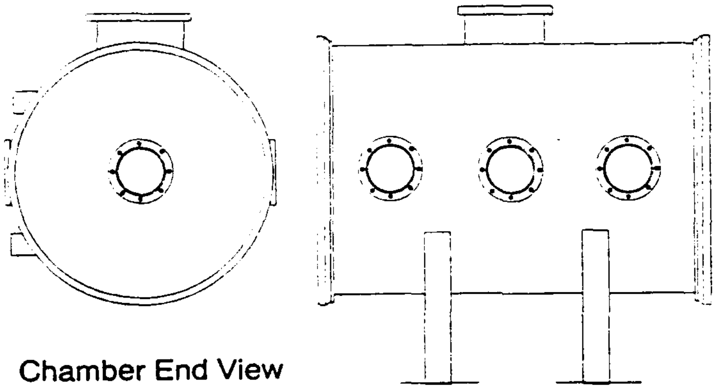


Figure 2
Arcjet Facility End View



Chamber End View

Chamber Side View

Figure 3
Chamber #4 (Optical)

ter end caps. Penetrations are cut corresponding to view port and vacuum duct size and location. A coolant flow up to 100 gallons per minute will be used to dissipate up to 100 kilowatts of waste heat. The water will be circulated through a Trane chiller unit (Model CGADC504AAD1DGHRT). The cooling panel configuration was selected to provide the best heat transfer possible, with minimal interference to viewing or experimental set-ups.

The endurance test chamber is a High Vacuum Equipment Corp chamber. The chamber is an 8 foot long, 6 foot diameter 1/4 inch steel chamber. The door, which moves on rails, has one 18 inch view port. On each side of the chamber is a 6 inch view port. The vacuum duct is located at the rear of the chamber along with instrumentation feedthroughs. The test chamber has built-in steel cooling panels that can take a coolant flow of up to 50 gallons per minute. This provides the vital cooling for the extreme heat given off during endurance tests. Minimal view ports allow for maximum cooling panel coverage.

Power

The arcjet power will be supplied by two Linde PHC-601 power supplies, each providing up to 750 Amps at 250 VDC with less than 5 percent voltage ripple. An air cooled ballast resistor (Milwaukee Resistor Corp) capable of dissipating 100 kWe will be used in conjunction with the power supply to prevent damage in case of short circuit. Water cooled power cables are used inside the chamber, connecting the arcjet to the chamber power feedthroughs.

Data Acquisition

Since the arcjet facility is intended for long term testing, thruster operations will be run by a personal computer (PC) based

data acquisition system. The PC is a 20 MHz IBM AT compatible computer with a 40 megabyte hard drive. Three Metrabyte data acquisition boards are used: a PIO-96 96 line input/output card for AT; a DAS-16F Very High Speed Analog I/O Board; and a DDA-06 six channel D/A, 24 bit PI/O. The data acquisition and control program Labtech Notebook will be used to collect and reduce data. All power and propellant flow levels are set manually at the beginning of a test run because of the steady-state mode. The PC system will collect the data and monitor key inputs such as thruster power, propellant flow, coolant flow, coolant temperature, chamber pressure, vacuum pump operation, and chiller unit operation. If any key data falls above or below a certain tolerance level, the computer system shuts down the entire operation.

Propellant System

The facility has a capability for ammonia and inert gas propellants, but it is flexible enough to allow future modifications to hydrogen propellant. The propellant system consists of three 326 cubic foot ammonia T-bottles plumbed into one regulator-selector switch (Fig. 4). This allows continuous ammonia flow. Once the first bottle reaches a low level, the next bottle begins releasing propellant, allowing the first bottle to be replaced. The three propellant bottle system will require a new bottle of ammonia about every three days for 1 gps of continuous testing. The propellant bottle system is located outside the building to reduce potential safety problems such as gas leaks or explosion hazards.

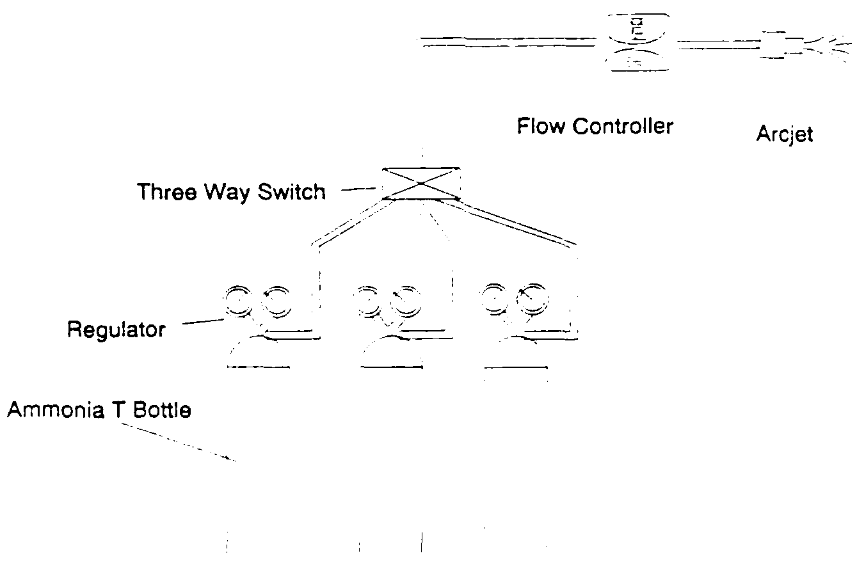


Figure 4
Propellant System

Transducers

A variety of transducers will be used to gather pertinent data. A Varian ionization gauge (Tube , Model 524-2, Controller,

Model 860A-2) measures the chamber vacuum pressure in the 10-100 millitorr range with an accuracy of +/- 5 percent. Propellant flow will be measured with a Micro Motion mass flow controller (Model DS006) for the ranges 0 to 1 gps of ammonia with a +/- 0.2 percent accuracy. Omega constantan alloy thermocouples will monitor thruster temperatures as well as coolant temperature. An Omega flowmeter (Model FP-5320CU) will monitor coolant flow.

A video camera located outside the vacuum chamber will record thruster firings and will allow frame grabbing for possible thermal imaging analysis. The camera records at a speed of 1000 frames per second.

Thrust Stand

The most important measure of rocket propulsion performance is thrust measure. This is true in electric thrusters as well, although in this case there are other considerations, such as required power system. Given that any electric thruster will take on the order of hundreds of days to achieve an operational orbit, a difference of a few extra days due to lower thrust may be acceptable if this eases system requirements.

Accurate thrust measurements are vital for comparing thruster performance, especially since other parameters such as specific impulse and electric power use efficiency depend on the thrust. Although indirect techniques exist for thrust measurement, most researchers use direct measurement. Even so, direct measurement of arcjet thrust poses several problems. The first is the fact that arcjet thrust is a small fraction of the thruster weight. Arcjet thrust is on the order of 1 pound, where a thruster may weigh 10-15 pounds. Any method used to measure the small thrust accurately needs to screen out the thruster weight effects. This is especially true because most arcjet thrust stands use some form of displacement to measure the thrust.

The second major problem is that of heat loads. Arcjets operate at very high temperatures. The anode temperature can reach up to 2300 degrees Celsius. For a 60 percent efficient thruster, almost 40 percent of the power goes into radiated and conducted heat. This heat is conducted through the thruster to the thrust stand. Heat is also radiated to chamber walls and the thrust stand. The heat adversely affects transducers used to measure thrust, while thermal gradients also distort thrust stand configurations and throw off calibrations.

A third issue is power transmission to the thruster. Heavy cables are usually required to handle the high powers. These cables not only add several pounds to the thruster, but they usually interfere with displacement measurement techniques.

Previous arcjet researchers have designed thrust stands to counteract these effects. JPL designed a water cooled pendulum arm with a set of weights that allowed remote calibration under vacuum (Ref. 6). The displacement was measured with a linear

variable differential transformer (LVDT). Heavy power cables were eliminated by using copper electrodes immersed in mercury pots. The weight and interference problem were solved, however problems with mercury evaporation existed. To prevent the evaporation oil was placed over the mercury. This slowed the evaporation, but over a long duration the oil hardened and began to interfere with thruster movement.

Researchers at Rocket Research Company have taken a different approach (Ref. 7). They have built a null balance water cooled arm. An LVDT senses thruster displacement and a personal computer based controller drives a solenoid that returns the thruster to its initial location. The applied voltage is proportional to the thrust. Although the arm is water cooled, there have been hysteresis problems in the data due to thermal gradients in the arm. Since the system is a null balance system, the cable interference is presumably negligible.

NASA-Lewis uses an inverted pendulum with a copper flexure to provide the equivalent of a restraining spring. The thrust is measured using an LVDT to find the pendulum displacement. The flexures also double as coolant lines to the pendulum arm. (Ref. 8).

At the PLEPL, we are including in-house development of an accurate arcjet thrust stand as part of the arcjet facility research goals. The intent is to build the simplest thrust stand possible, investigate the problems associated with the stand, and resolve them as part of the facility development. Towards this end, the PLEPL has designed a simple, cantilever beam thrust stand (Fig. 5).

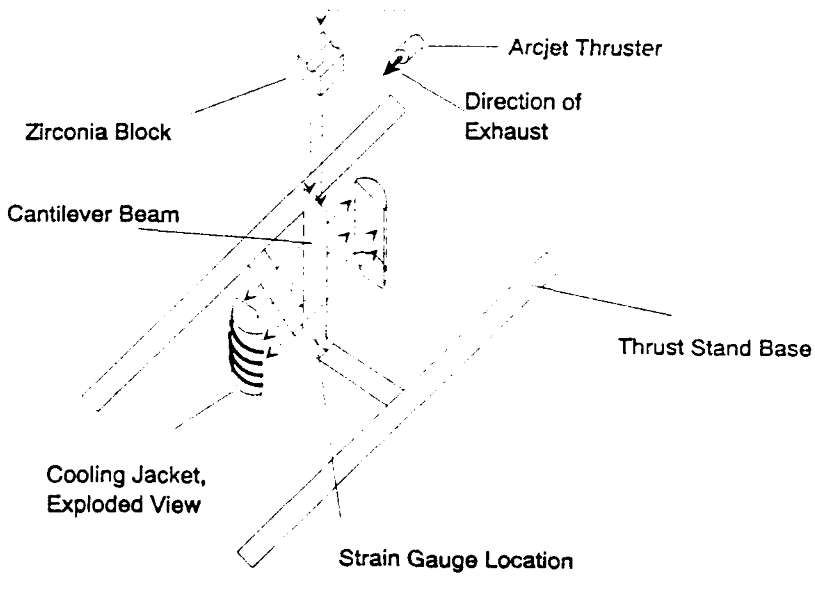


Figure 5
Thrust Stand Exploded View

The first form of the thrust stand is a cantilever beam, anchored at the chamber floor so as to bend along the thrust direction. A high temperature strain gauge set (Omega Model HBM 3/120 LF30) will be attached about a tenth of the length from the bottom. This will give the greatest strain while avoiding the non-linear strain at the beam attachment.

Although the strain gauges are high temperature, to avoid thermal problems we designed a zirconia block to hold the arcjet at the top of the beam. Ceramic zirconia has a thermal expansion of 12 [(delta L)/L/degrees C]*10E-6 and a thermal conduction coefficient of 2 W/(m*K). It also has an electrical resistivity of 10E8 Ohm-cm at room temperature. The zirconia block will keep the beam at a temperature of about 100 degrees Celsius. In addition, a water cooling jacket surrounds the beam to block radiative heating and to cool any propellant convective heating.

The zirconia block weighs 17 pounds, adding significantly to the weight at the top of the cantilever beam. In essence, the stand is a stiffened inverted pendulum. The large weight on top is much greater than the potential arcjet thrust. Although this arrangement is unstable and the thruster-block weight can overwhelm thrust measurements, it is hoped that the arcjet thrust will cause a perturbation that can be extracted from thruster-block weight through calibration. It may be found that the superb thermal advantages of the zirconia block are negated by poor thrust measurement resolution.

If the vertical beam is not satisfactory, the second attempt will involve a horizontal beam with the thrust along the horizontal and thus is the only force encountered (Fig. 6).

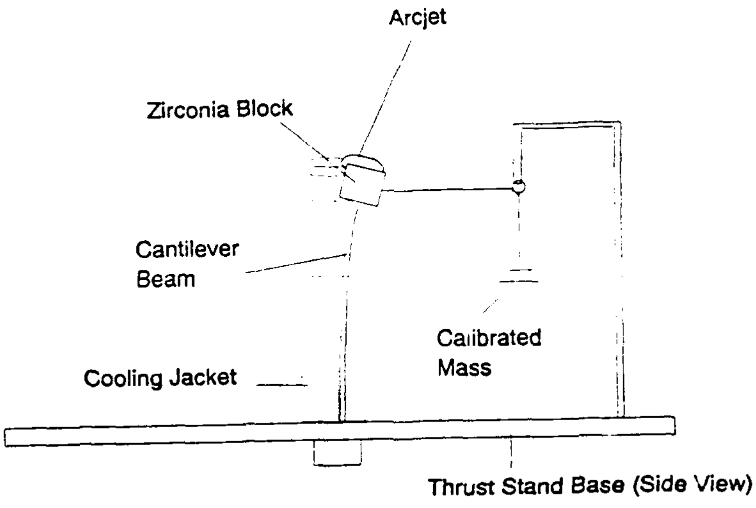


Figure 6
Thrust Stand Calibration Set-Up

If the zirconia block mass becomes a problem, then it will be removed and a lighter weight holder will replace it. This will greatly increase the heat load on the beam, resulting in the loss of strain gauge accuracy. If this is the case, then a LVDT will be used in place of the strain gauges to measure displacement. The LVDT, although suitable for high temperature, is still very susceptible to very high temperatures. A very low thermal conduction insulator will need to be placed between the LVDT and the beam. A cooling jacket may also need to be placed over the LVDT for similar reasons that one is needed for the beam, namely to shield the LVDT from radiative and convective heat.

Regardless of the displacement measurement technique, the same calibration procedure will be used. A set of known masses spanning the range of expected arcjet thrust will be applied in the direction of thrust (Fig. 7). The transducer voltage corresponding to the applied force will be taken and a calibration curve generated. This will be done in open air. Although no change in the curve is expected due to vacuum effects, as part of the facility check-out, vacuum effects on the calibration curve will be examined. The thruster will be fired while restrained to test for heat effects on the measured strain. The measured strain will be that solely due to heat loads. The question may arise as to coupling effects of heat and thrust on the strain measurement which may not be revealed by the restrained thruster test. To examine this, the thruster will be fired unrestrained with and without an attached mass. An approximate value of the thrust will already be available from the initial calibration. The calibration curve will also indicate what the measured value should be with the added mass. The only difference expected is the strain due to the additional heat load. Any extra strain is due to heat load-thrust interactions. If this extra strain is large enough to be significant, then it can be characterized and the thrust compensated by this technique.

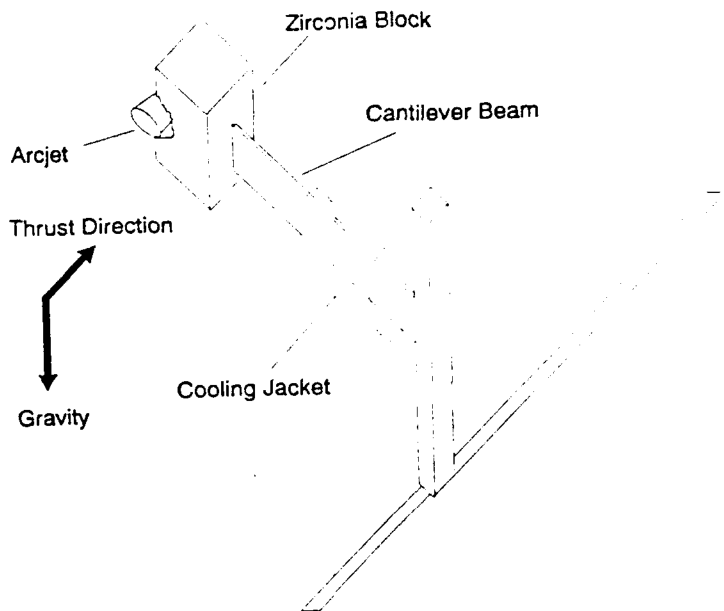


Figure 7
Side Mounted Thrust Stand

At the present time, the PLEPL does not want to deal with the safety and operational problems associated with a mercury pot power transmission system. The ensuing problems with thick, heavy cables must be accepted for the time being. Any possible damage to the power cable by heat will be prevented by the use of water cooled cables. These cables are quite heavy and stiff so they will have resistance to thruster motion. However, it is hoped that thruster displacement will be small enough that the spring force due to the cables will be minimal. It is also expected that in the vertical beam stand, the cables will provide enough resistance to the thruster-zirconia block combination to reduce the deleterious weight effects.

Arcjet Thruster

The arcjet thruster planned for initial check-out tests is the same design used in the Astronautics Laboratory's endurance test conducted by Rocket Research Company. This will allow comparison of PLEPL results with those attained by previous researchers. The 26 kW arcjet (Fig. 8) is composed of a tungsten anode and a 2 percent thoriated tungsten cathode. A boron nitride back plate with spiral propellant grooves guides the propellant into a small plenum. This arrangement swirls the gas, a known technique for stabilizing the arc. A conical tipped cathode is juxtaposed against the nozzle constrictor. From this constrictor, a constant area channel opens into a conical nozzle. The propellant is swirled into the constrictor channel, where the electric arc heats it. The heated gas is then expanded through the nozzle.

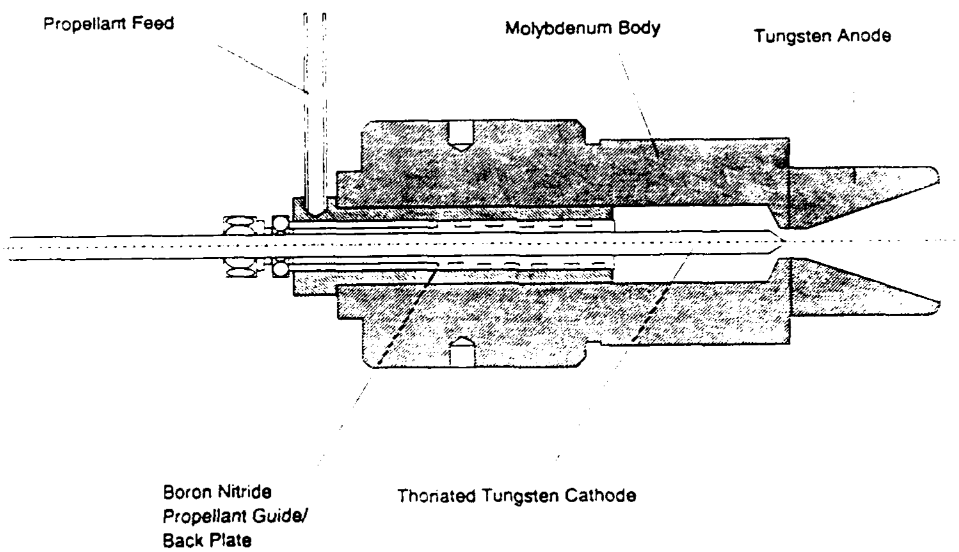


Figure 8
Arcjet Thruster Schematic

FACILITY CHECKOUT

An extensive series of check-out tests will be conducted on the facility to ensure optimal operation. Tests include vacuum operation check-out, heat removal, data acquisition, thrust stand operation, and diagnostic characterization of the arcjet chamber. Prior to endurance testing, the autonomous capability of the facility will be fully tested.

The vacuum tests will be the usual pump operation, leak tests, and isolation valve tests. They will also include measures of lowest vacuum attainable for given ammonia mass flows. Although ion gauges will measure chamber pressure, the chamber pressure-ammonia mass flow curves will give a ready reference as to what pressures may be expected for given mass flows.

Heat removal will be investigated by firing a thruster while reading coolant temperatures entering and leaving the cooling panels, along with the measure of the coolant mass flow. A complete thermal characterization of the chamber will be completed. This will entail taking thermocouple and pyrometer measurements over a broad range of the chamber. A very detailed thermal checkout will be taken on the thrust stand and thruster itself. System safety check thermocouples will be kept at the stand permanently.

The data acquisition system will be set up to take inputs from all transducers and perform system safety checks. A computer program will monitor key inputs and determine system safety. The computer controller will be connected to the power supplies and isolation valve controls and will end testing if a dangerous condition is detected.

The electric and magnetic fields around the firing thruster will be characterized in an electromagnetic map of the chambers similar to the thermal map. This will not be done in great detail, since that is the role of the arcjet plasma diagnostics project. The map will simply give an order of magnitude feel for the fields generated in the chambers to allow researchers to better plan their experiments, since they will know which effects to expect.

SAFETY CONSIDERATIONS

There are various hazards associated with the arcjet facility. The first is electrocution and electrical fires. This is to be expected, given the massive electrical requirements of electric propulsion devices. The first step in avoiding problems is to make sure that the power supplies are properly grounded. It may also help to elevate the power supplies above the ground on a suitable insulator such as wooden bars. Elevation would prevent short circuits in case of a water leak in the coolant system or triggering of the lab's water sprinkler system. This will also prevent electrocution of people in contact with the flooded floor.

An additional way to prevent electrical fires is to ensure that the power cables are properly insulated and connected. Cables should be covered with a metal conduit or cage, out of the way of traffic to prevent inadvertent contact and tripping hazards.

A properly grounded vacuum chamber will prevent dangerous charging developing on the chamber. Otherwise there is an additional electrocution danger to personnel in contact with the chamber.

Hazards associated with the ammonia propellant include asphyxiation, poisoning, and explosions. Asphyxiation is unlikely given the small mass flows, but any gas can displace oxygen in a confined space. The greater problem is ammonia poisoning. Ammonia in amounts greater than 500 parts per million (10 minute exposure) is toxic. To avoid both asphyxiation and toxic hazards, ammonia and oxygen deficiency detectors will be placed around the facility to monitor levels. Linked to the data acquisition system, the detectors will allow shut down of a test if dangerous levels are found. Explosive concentrations will also be detectable.

Another problem is that ammonia is reactive with copper and zinc, including their alloys (Ref. 9). This is important to consider for components in long term contact with ammonia. However, for short exposures or for properly insulated surfaces there should be no major problems.

Dangerous ammonia concentrations at the exhaust will be handled by dilution with air, which is the standard practice and is suitable for the small mass flows associated with arcjet research. An exhaust stack will be placed about ten feet above ground level to prevent direct access to the concentrated exhaust. Although passive dilution with air will most likely suffice, an 18 inch stainless steel, explosion proof fan may be placed at the exhaust to actively dilute the propellant.

The final possible hazard is a heated chamber. Although the cooling panels should take up most of the waste heat, some sections of the outer chamber wall may be exposed to radiative heating, causing a section of the chamber to be hot enough to burn. Or the cooling system may fail, ensuring that the chamber will be dangerously hot to both personnel and equipment. The latter problem will be avoided by monitoring coolant system performance. The problem of spot heating will be avoided by being cautious around the chamber when a test is in progress. Also, the thermal characterization should give an indication of where these hots spots are located.

CONCLUSION

The PLEPL has designed and begun installation of a two chamber arcjet facility, thus establishing a national capability for the development and understanding of arcjet thrusters. The facility will permit endurance testing of up to 1500 continuous hours. Also non-intrusive plasma diagnostic techniques for arcjet thrusters will be developed.

REFERENCES

1. Jahn, R.G., Physics of Electric Propulsion, McGraw-Hill, 1968.

2. Pivirotto, T.; King, D.; Deininger, W.; Brophy, J.; The Design and Operating Characteristics of a 30 KW Thermal Arcjet Engine for Space Propulsion, AIAA-86-1508, 22nd Joint Propulsion Conference, Huntsville, Alabama, June 16-18, 1986.

3. Cassady, R.J.; Lichon, P.G.; King, D.Q.; Arcjet Endurance Test Program, AL-TR-90-069, AL, Edwards AFB, Mar 1991.

4. Cassady, R.J.; Lichon, P.G.; King, D.Q.; Arcjet Endurance Test Program, AL-TR-90-069, AL, Edwards AFB, Mar 1991.

5. Pivirotto, T.J.; King, D.Q.; Brophy, J.R.; Deininger, W.D.; Performance and Long Duration Test of a 30 kw Thermal Arcjet Engine, AFAL-TR-87-010, AFAL, Edwards AFB, Nov 1987.

6. Pivirotto, T.J.; King, D.Q.; Brophy, J.R.; Deininger, W.D.; Performance and Long Duration Test of a 30 kw Thermal Arcjet Engine, AFAL-TR-87-010, AFAL, Edwards AFB, Nov 1987.

7. Cassady, R.J.; Lichon, P.G.; King, D.Q.; Arcjet Endurance Test Program, AL-TR-90-069, AL, Edwards AFB, Mar 1991.

8. Haag, T.W., Design of a Thrust Stand for High Power Electric Propulsion Devices, NASA TM-102372, NASA Lewis Research Center, Cleveland, Ohio, July, 1989.

9. Material Safety Data Sheet.